

Manufacture of a Four-Sheet Complex Component from Different Titanium Alloys by Superplastic Forming

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Abstract. A superplastic forming (SPF) technology process was deployed to form a complex component with eight-pocket from a four-sheet sandwich panel sheetstock. Six sheetstock packs were composed of two core sheets made of Ti-6Al-4V or Ti-5Al-4Cr-4Mo-2Sn-2Zr titanium alloy and two skin sheets made of Ti-6Al-4V or Ti-6Al-2Sn-4Zr-2Mo titanium alloy in three different combinations. The sheets were welded with two subsequent welding patterns over the core and skin sheets to meet the required component's details. The applied welding methods were intermittent and continuous resistance seam welding for bonding the core sheets to each other and the skin sheets over the core panel, respectively. The final component configuration was predicted based on the die drawings and finite element method (FEM) simulations for the sandwich panels. An SPF system set-up with two inlet gas pipe feeding facilitated the trials to deliver two pressure-time load cycles acting simultaneously which were extracted from FEM analysis for specific forming temperature and strain rate. The SPF pressure-time cycles were optimized via GOM scanning and visually inspecting some sections of the packs in order to assess the levels of core panel formation during the inflation process of the sheetstock. Two sets of GOM scan results were compared via GOM software to inspect the surface and internal features of the inflated multisheet packs. The results highlighted the capability of the tested SPF process to form complex components from a flat multisheet pack made of different titanium alloys.

INTRODUCTION

Superplastic forming (SPF) is an advanced metal forming technique to expand or stretch a metal without rupture under certain forming conditions (e.g. temperature, pressure, and strain rate) well beyond its plastic strain yielding limit at room temperature by applying a differential forming pressure from at least one gas manifold [1]. The manufacture of multisheet sandwich panel is an art applied via an SPF press, peculiar to certain metals. SPF is used to inflate sheet metals overlaid in a sheetstock form into a complex structure with novel characteristics, including component's high-strength-to-structure-weight ratio, stiffness, corrosion resistance and usable ductility, coupled with low density and relatively low manufacture cost. Some of the applications for SPF's sandwich panels are hollow airplane engine aerofoil blades, wing panels, jet engine exhaust structures, access aircraft door panel, satellite fuel tanks, and other honeycomb structures [2].

In the last decades, many researchers have been striving to create their own multisheets SPF techniques for specific applications or to obtain patents on their embodiments. Hamilton, and Ascani employed concurrence SPF and diffusion bonding (DB) techniques for the manufacture of complex variable-thickness metal structures (e.g. honeycomb structures) from Ti-6Al-4V titanium alloy blanks [3]. However, they produced the component's core panel by conventional manufacturing techniques prior to utilizing SPF/DB process to press two metal face sheets over the core panel. Froes and Eylon [4] received a patent for their embodiments for suggesting forming several titanium alloy SPF/DB components, particularly structural panels, by bonding different partially shaped parts (e.g. honeycomb,

waveform, cups, patterned coatings) as core structure to two face sheets. Researchers at the AFRC of the University of Strathclyde in UK developed an SPF/DB technique to form the jet engine fan blade by assembling three Ti-6Al-4V sheets structure in which a single inner core sheet was bonded to two skin sheets [5]. Kistner and Will [1] introduced SPF with an adhesive bonding (AB) technique to produce four-sheet aluminium alloy sandwich structures with a pattern of internal walls parallel to one edge of the panel. Velicki patented his work for manufacture a hollow core fan blade for a gas turbine engine using a four- Ti-6Al-4V sheet structure via an SPF/DB process after preparing the core sheet stack via bending, folding, TIG welding and roll seam welding operations [6]. Hayase et. Al. invention for the McDonnell Douglas Corporation [7] employed a biaxial intermittent or discontinuous seam weld pattern to bond four sheets of the same type of titanium alloy in a predefined pattern to produce the first sandwich structure with a plurality of the pocket core configurations. They used one pipe gas inlet SPF to form only the core sheets to their final shape, while the dies hold the face sheets at the predefined position, to generate DB between the core and face sheets. The main objective of the aforementioned SPF works was to adapt low strain rate range and high tensile elongations deformation to minimize necking during the material flow due to the inflation process [1-7].

In this paper, an SPF process was employed to form a complex eight-pocket sandwich panel component from a four-sheet titanium alloy sheetstock. The development of the sandwich panel adopted pioneering work in SPF research due to some aspects of the manufacturing process. Six flat multisheet packs were assembled from three different titanium alloys in three core-skin sheet combinations to be formed under two simultaneous pressure cycle profiles. Unlike the major work in this research topic, the SPF process in this work was also applied to titanium alloys other than Ti6Al4V, and multiple gas pressure curves were simultaneously used for forming core and skin sheets. The SPF process was controlled by optimized pressure-over-time loading via finite element method (FEM) analysis and destructive testing at 900 °C.

FABRICATION OF THE SHEETSTOCK

The material selected for this work were Ti6Al4V, Ti6242, and Ti54M titanium alloys in sheets of 457 x 457 mm in size. The sheets were inspected visually to assure they were defect-free. The chemical composition of Ti54M are 5%Al, 4%Cr 4%Mo, 2%Sn, 2%Zr in titanium matrix, with special attributes of heat-treatable, deep section hardenability, very high strength Ti alloy superior strength and creep resistance over Ti64 to up to 400 °C. The main elements in the chemical composition of Ti6242 are 6% Al, 2% Zr., 4% Mo, 2% Sn with extra low interstitial (ELI), and its application is in high-temp jet engines parts (e.g. blades, discs, spacers, seals), high performance automotive valves. Ti64 is the most common applied titanium alloy with main chemical component of 6% Al and 4 % V with ELI, offering improved ductility and fracture toughness in air and saltwater environments [8]. Thereof, the sheets have different ductility attributes which affect their manufacturing and forming processes. Each sheetstock was arranged to consist of four sheets: two core sheets from the same material, which create the inner structure of the panel, two skin sheets from the same material, which form the outer structure of the panel. Ti64 and Ti54M titanium alloy sheets were used for the core sheets, whereas Ti64 and Ti6242 titanium alloy sheets were used for the outer sheets of the packs. Each sheetstock combination was designated with a pack number as shown in Table 1.

TABLE 1. Multisheet Pack Material Configurations

Combination number	Pack ID	Surface Sheets		Skin Sheets	
		Material	Thickness [mm]	Material	Thickness [mm]
C1	P#1, P#2, P#3	Ti6Al4V	0.8	Ti6AL4V	1
C2	P#4	Ti6Al4V	0.8	Ti6242	1
C3	P#5, P#6	Ti54M	0.625	Ti6242	1

After assigning the zero-point parameters for the machining process, all core sheets were cut using a water jet machine to have a V-notch at one side for internal inlet gas pipe installation. The core sheets welding pattern was designed to create eight internal separate cells between two core sheets. The inner sheets were welded together using intermittent resistance seam welding to create small gas passages between two adjacent cells. The passages were designed to allow the pressured gas to flow from the inlet gas pipe to all cells between the core sheets during the SPF process. The outer sheets were then welded around the perimeter on either side of the already welded inner sheets

except in the area where the second gas inlet connected to the sheetstock. Then, the second gas inlet was welded to the flat packs to enable the application of the second SPF pressure-time cycle. The length of the unwelded line on the welding pattern was determined based on the die design in the inlet pipes with a 28 x 2.5 mm rectangular area for both gas inlet pipes for core and outer sheets. Figures 1 (a) and 1(b) depict the schematics of the welding patterns to join the core sheets to each other and the outer sheets with the core sheets, respectively. Figure 1 also shows the location of the gas inlet pipes welding between the core sheets (Figure 1-a) and between the core panel and the external sheets in the final structure of the sheetstock (Figure 1-b). The gas pipes were welded to the sheets by TIG welding. Figure 2(a) shows a picture of the welded core sheet with the inlet gas pipe in the manufactured pack. Then, as it can be seen in Figure 2(b), two skin sheets are welded to the core panel according to the arrangements described in Table 1 and welding pattern shown in Figure 1(b) to complete the six flat multisheet packs. All flat packs were brought to vacuum and then pressurized to one bar using Argon gas prior to applying the SPF pressure cycles to ensure the absence of leaks on the welding lines or around the inlet gas pipes.

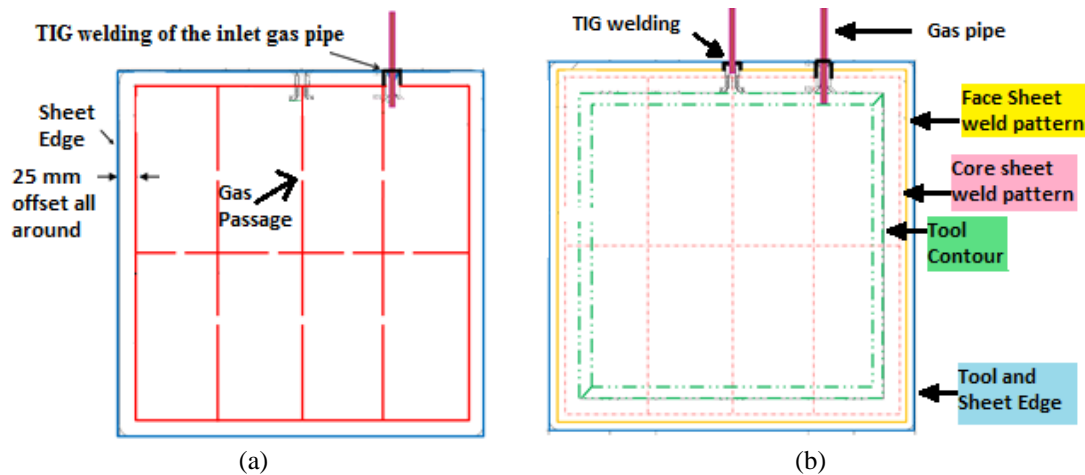


FIGURE 1. Schematic view of resistance seam welding over (a) core sheets and (b) skin sheets.

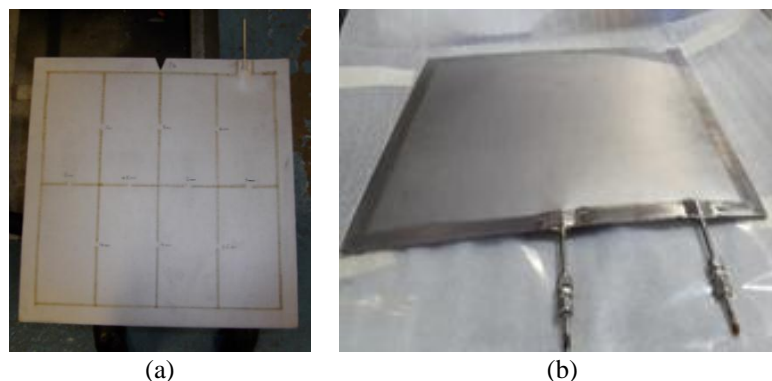


FIGURE 2. picture of a manufactured (a) core sheet panel and (b) flat multisheet pack.

SUPERPLASTIC FORMING PROCESS

Three dimensional models of the top and bottom dies designed in SolidWorks software. The die material was stainless steel suitable for high temperature forming. Each die was estimated to have 153 kg weight. The dies in the later design were mounted to the SPF platform by sixteen screws with machining tolerance of 0.1 mm for bottom and top die to secure the dies during the SPF process. The dies were machined in a vertical 3 axis CNC machine at COMAC Company. A coordinate measuring machine (CMM) report was provided for each die following machining to meet the die symmetry and tolerances of the fixing points. Each fixing point was checked with a screw gauge following machining. Pin gauges were used to verify the thermocouple port diameters of the dies. GOM scanning of the dies

(Figure 3) verified the feature dimensions by comparing the scans with the three dimensional design models. The colour map in Figure 3 shows the deviation of the manufactured die from the designed model

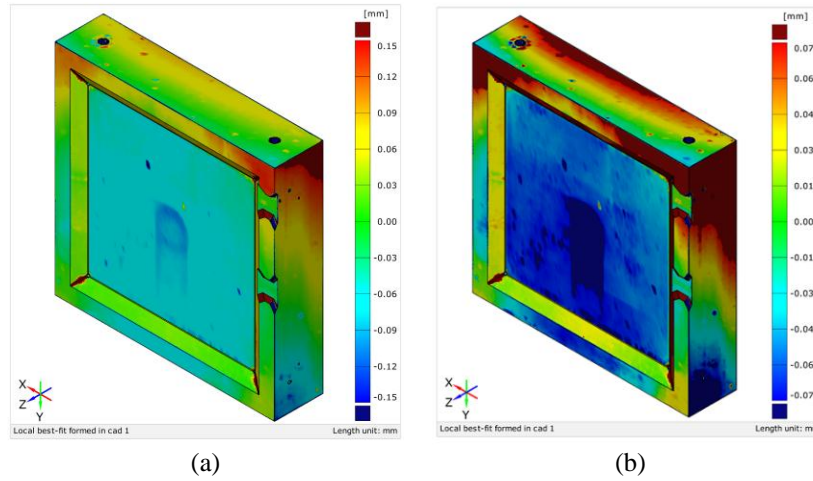


FIGURE 3 CMM measurements of (a) top and (b) bottom dies

One of the key aspect of an SPF process is the pressure cycle defined for a desired structure which need to be determined specifically for each material to be formed. The sandwich panel sheetstock and the dies were modelled separately for each pack combination of Table-1 using FEM modules in ABAQUS software package. Constrains of the models were the dies surfaces, the blank holders, and the welding lines over the core and skin sheets determined by the welding patterns shown in Figure 1. A time-hardening model in ABAQUS software was used to implement the superplastic creep behaviour of the materials in the simulation. The time hardening equation known as Bailey-Norton law demonstrated a better curve fitting for the experimental results obtained in comparison with other built-in models in the software such as the strain-hardening model and the hyperbolic strain model. The forming process involved two pressure cycles acting simultaneously through two inlet gas pipes on the flat packs to inflate in turn the external and core sheets of the sheetstock structure. The first pressure cycle (P_1) was used to inflate the outer sheets into the shape of the die cavity. The second pressure cycle (P_2) was used to expand the inner sheets and create the core panel cells structure. During the forming process the pressure cycle P_1 increased and, once it formed the outer sheets, decreased to zero. The pressure cycle P_2 was applied until the inner sheets were in contact with the outer sheets on the die surface and the internal core structure was fully formed. Since both cycles were acting simultaneously, the pressure cycle acting on the outer sheets (P_1) also acted against the pressure of the inner sheets (P_2). This meant that the effective inner pressure cycle (P_E) is the sum of both pressure cycles (i.e. $P_E = |P_1 + P_2|$). The effective inner pressure cycle allowed the packs to be fully formed and developed into the inner cell structure. The pressure cycle for each combination of sheets listed in Table-1 was initially developed using FEM models for a target strain rate of 0.0002 s^{-1} at 900°C . Each pressure cycle was then adjusted and optimized during the trials following GOM scanning and cutting the packs for visual inspection. To this purpose, each inflated pack was scanned by GOM ATOS Triple Scan III at room temperature. Then, the packs were cut along longitudinal and transverse directions to investigate the inflation of the core sheets. The following trial's pressure cycle was optimized based on the geometrical analysis of the packs previously formed. Therefore, one unique pressure cycle was designed for each of the pack after each optimization to have fully formation of the core panel or improve DB/SPF level. Consequently, different pressure cycles were applied to the packs with the same sheets combination of C1 and C3 in Table-1.

The multisheet packs were formed in an ACB Loire 200T SPF press at the AFRC, as previously described. All surfaces of the flat packs were coated with boron nitride to prevent the sheets from sticking to the die surfaces due to the compression forces at elevated temperature and to facilitate removing the pack from the dies after forming. The ram force was set to 30 ton based on previous SPF experiments and to enhance the results of the diffusion bonding effect. A number of other SPF press parameters were necessary to be set precisely for a successful inflation, e.g. ram speed and ram position. Six thermocouples were used to control the homogeneity of the temperature inside the die cavity during the SPF process.

RESULTS AND DISCUSSIONS

The software of the 200T SPF press controlled the parameters of the inflation process based on the built-in and operator's program set points. The accuracy of the inflation method was reviewed using the GOM Inspect V8 software package to inspect the forming packs. The GOM Inspect software generated contour map by comparing the formed pack with the required surface and internal features derived from three dimensional design models and numerical simulation analysis.

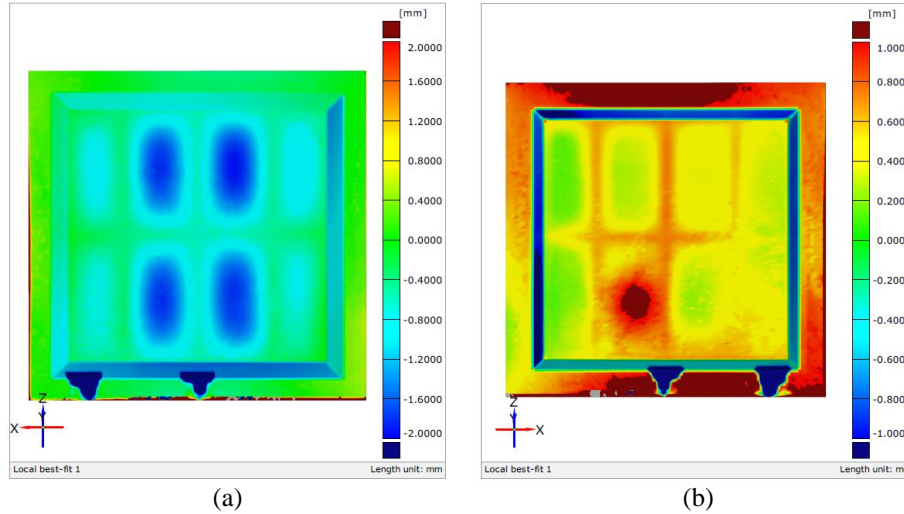


FIGURE 4. GOM colour map deviation between formed pack and the FE simulation models on an inflated multisheets pack for (a) top side and (b) bottom side of the formed pack.

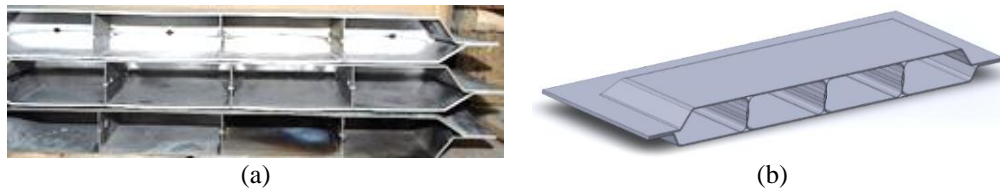


FIGURE 5. Cross-section view of the formed packs after cutting: (a) picture and (b) GOM scan.

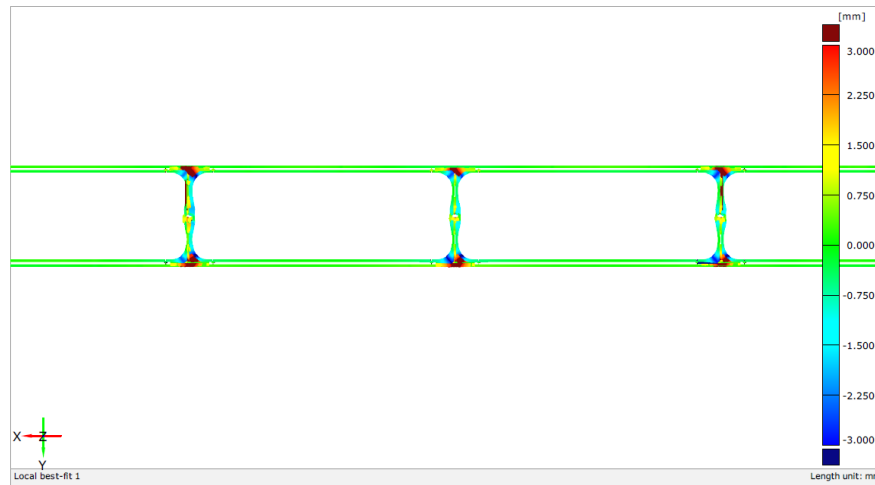


FIGURE 6. GOM deviation map for comparison between the FE simulation model and the scan of a formed packs.

Initially, several CAD drawings were produced based on the FE results. These drawings were then used to produce SolidWorks models to be used as a reference for comparison with the GOM scan results. Figures 4(a) and 4(b) show the deviation of the GOM scans of the formed packs from the predicted final geometry derived from the FE results for the top and bottom dies, respectively. The traces of all eight internal cells in Figure 4 indicate possible well-formed internal cores. This type of analysis was performed for all six inflated multisheet packs. These analyses highlighted almost the same range of discrepancy between formed pack and the FE prediction. This confirmed that the external sheets were fully formed according to the FE results. After cutting the packs, it was possible to observe that not all core panels fully formed. However, their geometry was very similar to the FEM simulation results for the core panel at different time steps of the simulations. Figure 5 shows a picture and GOM scan of a cross-section of a formed pack and highlights the internal features of the component. A second set of GOM scans was performed on all multisheet packs after cutting transversally. Figure 6 shows the GOM scan of a cross-sections of one of the formed pack in comparison with the FE simulations models. The colour scale shows the deviation of the formed walls between the pockets from the geometry required by the FEM simulations due to the inflation of the core sheets.

SUMMARY AND CONCLUSIONS

An SPF manufacturing process was introduced for forming multisheet sandwich components composed of different titanium alloys for skin and core panels. SPF trials were performed to inflate six flat sheet stocks to a complex eight-pocket sandwich panel geometry within SPF dies. The sheetstock packs were assembled in three different combinations with two materials for the core sheets -Ti64 or Ti54M -titanium alloy, and two materials for the skin sheets - Ti64 or Ti6242 - titanium alloy. The welding patterns on the flat multisheet packs were designed precisely to produce the required final structure by means of intermittent and continuous resistance seam welding manually controlled for bonding the core and skin sheets, respectively. An optimized SPF with two simultaneous pressure cycles was designed to form both skin and core sheets at the same time. A time hardening creep model was embedded into FEM simulations to evaluate the final component inflation based on the die three dimensional models and sandwich panel geometry. From the comparison between the GOM scan of the inflated packs and the FE results, it was deduced that the implemented FE approach was able to capture the flow of material reasonably close to the formed packs. The same procedure could be implemented to manufacture sandwich panels with more complex core configurations from sheetstock composed of more than three sheets. The suggested SPF process could also be suitable for forming complex structures from sandwich panels out of other metal alloys with high ductile characteristics under SPF parameters. The final results of this work are promising in order to achieve reasonable costs and to shorten the time for manufacture complex multisheet titanium alloy components with novel characteristics.

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